

Relation between M_{BH} and M_{bulge} : A simulation study

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ABSTRACT

The dynamical evolution of super star clusters (SSCs) moving in the background of dark matter halo has been investigated as a possible event causing the observed correlation between the mass of galactic bulge, M_{bulge} , and the mass of its central black hole, M_{BH} . The involved physical processes are the sinking of SSCs due to the dynamical friction, and the stripping of SSCs on their way to the center. Model calculations show that only sinking of circum-nuclear SSCs contribute to both the growth of the central object and the formation of the galactic bulge at the early stage. On the assumption of a universal density profile for the dark matter halo, and an isothermal model for the SSCs, our simulations have yielded the mass ratio of the central objects to the bulges formed this way to be about a few times 10^{-4} , less than the observed median value for early type galaxies. It is, however, consistent with the observed mass ratio for disk spirals, implying that the proposed scenario might be a possible event for the formation of bulges and central black holes of late type galaxies and for $M_{BH} - M_{bulge}$ correlation of disk galaxies.

Key words: black hole physics – Galaxy: center – Galaxy: bulge – Galaxy: kinematics and dynamics

1 INTRODUCTION

Recent observations with unprecedented high resolution have firmly established that many galaxies, whether active or not, host supermassive black holes (SMBHs) in their centers (Ko-

rmendy & Richstone 1995, Kormendy & Gebhardt 2001). These observations have revealed correlations of the mass of the SMBHs to the luminosity (or mass) of their bulge (Kormendy & Richstone 1995, Magorrian et al. 1998, Wandel 1999), or to the luminosity-weighted line-of-sight velocity dispersion within the effective radius with much smaller scatter (Gebhardt et al. 2000, Merritt & Ferrarese 2000). However, no correlation has been found between the BH masses and the total luminosities of host galaxies (Kormendy & Gebhardt 2001). The median black hole (BH) mass is 0.13% of the mass of the bulge (Kormendy & Gebhardt 2001) for early type galaxies, or much smaller for late-type spirals (Salucci et al. 2000, Kormendy & Gebhardt 2001, Gebhardt et al 2001).

The latest observations with X-ray Observatories provide evidence showing that the formation of black holes is connected with starbursts (Matsumoto et al. 2001, Fabbiano et al. 2001, Strickland et al. 2001). Matsumoto et al. (2001) and Strickland et al. (2001) argued that there exist intermediate-mass black holes (MBH) in the off-nuclear compact X-ray sources in M82 and NGC3628, respectively. The formation of SMBHs through these MBHs has been explored soon after (Ebisuzaki et al. 2001). Haenelt & Kauffmann (1999) have also studied the relation between SMBHs and the formation of galaxies. On the other hand, a beam model has been proposed (King et al. 2001) to ease the difficulties that the unbeamed models run into, where MBHs are required.

The correlation between the mass of SMBHs, M_{BH} , and the mass of the bulge, M_{bulge} , implies that the growth of the central BH and the formation of the bulge are probably caused by a same physical process, or event (e.g. Kormendy & Gebhardt 2001). This "event", however, has not been clarified yet.

In this paper, we report our study on the dynamical evolution of circumnuclear SSCs moving in the dark matter halo as a possible "event" for the observed relation of M_{BH} to M_{bulge} . We find that the sinking of the SSCs, along with the tidal stripping on their way to the center, could contribute to simultaneous growth of M_{BH} and M_{bulge} . Based on a set of reasonable parameters, the mass ratio M_{BH}/M_{bulge} derived from our numerical simulations coincides with the observed values of disk spirals.

2 MODELS

2.1 SSC model

Recent observations of starburst galaxies with high resolution have revealed that there are many compact, young and very luminous SSCs in the central regions of galaxies (Shaya et al. 1994, Surace et al. 1998, Surace & Sanders 1999, Whitmore et al. 1999, Scoville et al. 2000, de Grijs et al. 2001). Numerical simulations have also shown that interaction or merger among galaxies can trigger strong starbursts around the nuclear regions. While galaxies are merging or interacting, some gas components could lose their angular momentum and fall into the central region (Mihos & Hernquist 1996, Barnes & Hernquist 1996). Then, rather high pressure of the warm interstellar gas could induce global collapse of giant molecular clouds and thus forming circumnuclear SSCs (Jog & Solomon 1992, Harris & Pudritz 1994).

On the one hand, there exist some observational facts about SSCs, but not many conclusive results about their dynamical properties are reached so far. On the other hand, the SSCs are believed to be the progenitors of present-day globular clusters (GC) (e.g. Smith & Gallagher 1999, Origlia et al. 2001). It would then be reasonable to model SSC by using both clues mentioned above. We assume that SSCs have a similar mass spectrum as the initial GC mass function but with larger mean value. According to Vesperini (2000,2001), we take the following log-normal mass function for SSCs (SSCMF), with its mean at $5 \times 10^6 M_\odot$ following the investigations on SSCs (e.g. Surace & Sanders 1999, Origlia et al. 2001, Surace et al. 1998, Cen 2001, Meylan 2001),

$$\text{Log}_{10}(M) \sim N(\exp(\text{mean}) = 5 \times 10^6, \text{variance} = 0.08) \quad (1)$$

With this SSCMF, we generate randomly 100 sets of SSCs, each containing 100 SSCs (for taking 100 SSCs, see Combes 2001, Fellhauer 2001, Whitmore et al. 1999).

For simplicity, an SSC is modeled as a truncated isothermal sphere with three parameters: the central density (ρ_c), the velocity dispersion (σ) and the initial truncated radius (R_0). Taking a lower and an upper limits of ρ_c to be $5.3 \times 10^3 M_\odot/pc^3$ and $3.4 \times 10^4 M_\odot/pc^3$ from observed ones (Larsen et al. 2001, Campbell et al. 1992), we assume a linear function of cluster mass, M , for $\rho_c(M)$. And with R_0 taken to be the local tidal radius, σ can be derived from M and ρ_c . The resulted σ also increases with M .

The initial distribution and evolution of SSCs in a starburst galaxy is not clear, though it is very important for the problem we are investigating. In our simulation, all of the 100 circumnuclear SSCs in each set are initially placed at a distance of $1kpc$ from galactic center, typical locations for circumnuclear SSCs, and assigned with local circular speed. As will be

discussed in the last section, we also tried larger distance and found that more distant SSCs are generally irresponsible for the formation and early growth of bulge and central compact objects.

2.2 Background

As we are considering the formation process of bulge and central massive objects, the dark matter dominates not only globally, but also in the central region at early stage. Therefore, only dark matter halo is considered initially in our simulation. For the dark halo, we assume the universal density profile (Navarro, Frenk & White 1997), which can be written as (e.g., Binney et al., 1998)

$$\rho_h(r) = \frac{M_{0h}}{r(a_h + r)^2} \quad (2)$$

where r is the distance from the halo center, and, a_h and M_{0h} are two parameters. The value of a_h is connected with the extension of the halo and it may change with time. However, how it changes is not well quantified. So, we take two rather different values of a_h for comparison. Later, we will see that the results are not too much different, and so, acceptable. Besides, since we are concerned with the formation and the early growth phases of galactic bulge and its massive central objects, of which the time duration is taken to be $1Gyr$, a_h might be well approximated as time-independent. Following El-Zant et al. (2001), we take $a_h = 6kpc$ and $10kpc$, and, M_{0h} is derived from a_h with the condition that there are $10^{12}M_\odot$ interior to $200kpc$.

Our test calculations show that the first fallen SSCs, the massive ones in each set of SSCs, can contribute about $2 \times 10^4 M_\odot$ to the central globe of radius $1pc$, while in the same region there are dark matter of less than $10^3 M_\odot$. In the meantime, the mass in the innermost region (interior to a few $10pcs$ from the halo center) can be significantly changed by the fallen SSCs, although outside about $200pcs$ remains dark halo dominating. The background variation of this kind has substantial effect on the further mass contribution to the central region from stripped SSCs. In order to account for the effect of fallen SSC mass, which is characterized by a steeper mass density profile near the center than the universal one, a truncated singular isothermal sphere is added after the most massive SSC has fallen.

2.3 Dynamical friction

In the following, M and \vec{V}_M (with $V_M = |\vec{V}_M|$) denote, respectively, the mass and velocity of cluster experiencing the dynamical friction. Assuming a Maxwellian velocity distribution with dispersion $\sigma_{background}$ of background matter, composed of particles with mass much smaller than M , the dynamical friction formula writes (e.g., Binney et al, 1987)

$$d\vec{V}_M/dt = -\frac{2\pi \log(1 + \Lambda^2)G^2 M \rho}{V_M^3} [\text{erf}(X) - \frac{2X}{\sqrt{\pi}} \exp(-X^2)] \vec{V}_M \quad (3)$$

where erf is the error function, and,

$$\begin{cases} \Lambda = \frac{b_{max} V_{typ}^2}{GM} \\ X = \frac{V_M}{\sqrt{2}\sigma_{background}} \end{cases} \quad (4)$$

The quantity b_{max} is the so-called maximum impact parameter and V_{typ} a kind of typical module of the relative velocity between M and a background particle. Neither b_{max} nor V_{typ} is precisely defined. Fortunately, uncertainty in either quantity causes no significant difference in the resulted values of the dynamical friction. Following Binney et al. (1987), we use $b_{max} \equiv 2kpc$ and take $V_{typ} \equiv V_M$. The velocity dispersion $\sigma_{background}(r)$ can be roughly estimated from the Jeans equation.

2.4 Stripping

It is assumed that the stellar mass outside a sphere, the radius of which is denoted as R_t , approximating instant Hill stable region around the SSC center, will be stripped. Since the stripping is processed continuously as r (the distance between halo and SSC centers) decreases, only a thin outer layer is to be stripped at a time. Therefore, in an average sense, the stars stripped when the SSC goes from r to $r - dr$ are contributed to a region radially bounded by $r + R_t(r)$ and $r - dr - R_t(r - dr)$. As a first-order approximation, the mass of the stripped stars are considered to be, at some later epoch, uniformly distributed in the shell bounded by $r + R_t(r)$ and $r - dr - R_t(r - dr)$. By summing up all of the stellar mass stripped at various rs , the stripped stellar mass distribution can be derived. The SSC's mass contributed to the galactic center (taken as a globe with radius $1pc$) is just the remaining mass of the SSC when $r + R_t(r) \leq 1pc$ plus the previously stripped mass inside the above-mentioned $1pc$ globe.

Obviously, if a massive single object is embedded in the center of SSC, stripping cannot be proceeded further when only this object is left. X-ray observations discovered a lot of the

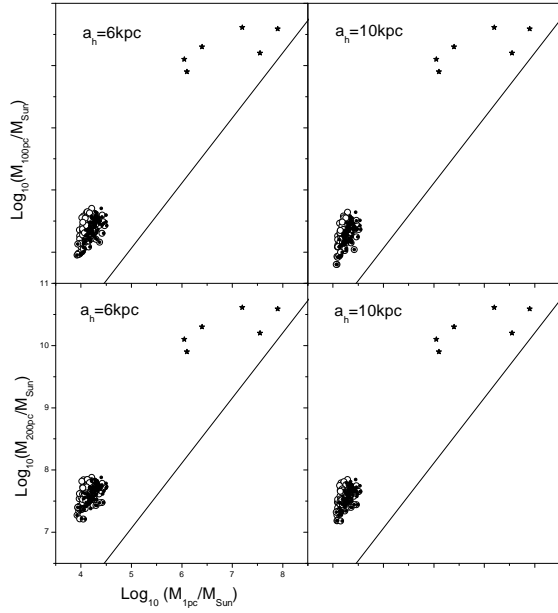


Figure 1. M_{BH} vs M_{bulge} . Legend: solid line — results for early type galaxies; \star — observational results for Sb-Im galaxies; open and filled circles — simulation results with and without non-stripped compact cores (or BHs) embedded in the SSCs, respectively.

so-called super-Eddington sources associated with SSCs (Matsumoto et al. 2001, Strikland et al. 2001). However, whether there are MBHs, ranges from several hundreds to about one thousand solar mass (Ebisuzaki et al. 2001), or the observations are only due to beam effect (King et al. 2001) is still not clarified. If massive black holes do form in SSCs, they would most likely be at the center of the SSCs. Therefore, in our simulations, we consider two extreme cases: the stripping is not allowed when the mass of the stripped SSC is less than $1M_{\odot}$ and $1000M_{\odot}$, respectively.

3 RESULTS

The results about the relation between SSCs' mass contributions to M_{bulge} and M_{BH} are summarized in Fig.1, where M_{1pc} , M_{100pc} and M_{200pc} are the mass contributions of the SSCs to the globes of radii $1pc$, $100pc$ and $200pc$, respectively. The observational results for early-type galaxies (Kormendy & Gebhardt 2001) and six Sb-Im galaxies (Salucci et al, 2000) are also shown. In our simulations, 94 - 96 percent of the SSC sets, each representing SSCs in a single galaxy, can contribute mass to the inner $1pc$ globe. Here we take two values, $100pc$ and $200pc$, for the radius of bulge. As shown in Fig.1, no substantial differences between these two cases. Noting further that the stripped SSC mass interior to $100pc$ is generally no

more a small quantity in comparison with the dark halo mass in the same region, to take $100pc$ as the radius of a bulge (or pseudo-bulge) form this way might be appropriate.

By comparing the left and right panels of Fig.1, one finds that $M_{bulge} - M_{BH}$ relation has no fundamental disparity for different values of a_h . This implies that similar results could be obtained for time-dependent a_h , regardless how it changes with time. Besides, the results for SSCs with and without central black holes are also similar to each other. This is because the mass of the formed central object of galaxy, much larger than that of the assumed SSC's central black hole ($10^3 M_\odot$), is mainly comes from the most massive SSC. As a result, the obtained $M_{bulge} - M_{BH}$ relation might be valid for generic very-late type disk galaxies, provided that the bulge-BH do form in this way.

As can be seen from Fig.1, M_{BH}/M_{bulge} in our simulation is smaller than that of the observed one for early type galaxies. And, as already stated, strong tidal force of galactic central object previously formed from the most massive SSC prohibits the non-single objects sinking into the $1pc$ globe. This implies that the bulge mass will be increased faster afterwards, and so, even smaller value of M_{BH}/M_{bulge} is expected at some later stage. Our results, however, consistent with the observational ones for disk spirals (Salucci et al. 2000, Kormendy & Gebhardt 2001, Gebhardt et al. 2001), implying that the proposed scenario of $M_{BH} - M_{bulge}$ formation might be valid for very-late type disk galaxies. Possibly, the $M_{BH} - M_{bulge}$ correlation for galaxies of various types of Hubble sequences might not be linear, which is a possibility discussed in the case of M33 (Gebhardt et al. 2001). To detect the BH masses of less than $10^6 M_\odot$ in galaxies would be crucial for deliberating the linearity of the $M_{BH} - M_{bulge}$ correlation.

4 DISCUSSION

In our simulation, we have made some assumptions either due to lack of knowledge or for simplifying the simulations.

An important assumption is that the background is composed of dark matter only, though we have considered the background variation later. Indeed, this assumption is compatible with what we investigate in this paper – the formation of bulges and the growth of central black holes at the early stage. In accordance with this, the SSCs we have studied are circumnuclear ones assumably originated from the mergers of very late-type galaxies. These galaxies are sources with disk components only. In this case the dark matter of a few times

$10^9 M_\odot$ dominates over luminous systems inside 1 kpc from the center. As a first step of our investigations, it would be reasonable to make such an assumption. On the other hand, it will be interesting to see what the theoretical correlation will be if more components are assumed, e.g. disks and a pseudo-bulge, in the background for our simulations. In other words, the logical, next step of our investigations is to study a way for the first formed bulge and the central BH to grow further, and to see what the ratio of M_{BH}/M_{bulge} will be. Probably, a new merger is needed. That is, a new merger occurs between two disk galaxies with small central BHs and pseudo-bulges. A study of this kind is under our consideration.

Another point we have not considered in our simulations is the distance distribution of SSCs, on an average of 1 kpc for circumnuclear SSCs. SSCs at different distance would make different contribution to both bulge and central object masses. M33 might be an example in favor of considering distance distribution for SSCs. A compact star cluster is observed to locate at its nucleus (e.g. Gebhardt et al. 2001), which is more like a GC based on its dynamical parameters (Kormendy & McClure 1993). The formation of this GC might find its way in the scenario proposed in this paper.

Besides, in our simplified treatments, we include no effects of non-spherical SSCs mass distribution, of background rotation, and of others. We'll cooperate these effects in our future studies.

The survival of SSCs over Gyrs is a key question for the scenario presented in this paper, which is also crucial for the hypothesis where the SSCs are progenitors of present-day GCs. This question has been analyzed by Origlia et al.(2001) for one SSC in NGC 1569, NGC1569-A1. They found that this SSC has a standard Salpeter initial mass function with no truncation at lower mass limit, implying that it can evolve into a system similar to the present-day GCs. Forbes, et al.(2001) have claimed recently that the formation of a bulge/spheroidal stellar system is accompanied by the formation of metal-rich GCs (red GCs). Adopting the scenario of SSCs as the progenitors of GCs, our proposed processes for the formation of bulge, i.e. through sinking of SSCs, along with the tidal stripping, thereafter might be a way for their claim.

We have also performed numerical simulations for the SSCs located far away from the center, without considering the effect of tidal stripping. The results show that these SSCs with masses of $10^6 - 10^7 M_\odot$ will stay in the external regions. Cen (2001) proposed that the external SSCs are formed from gas-rich sub-galactic halos triggered by the reionization of the universe. These young stellar systems with masses of $10^3 - 10^6 M_\odot$ are suggested

as progenitors of the present-day halo GCs (blue GCs). Our study on the external SSCs supports Cen's suggestion in the sense that they will stay well outside the galactic central regions.

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